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01 Aug 2006

Application of Chip-Level EMC in Automotive Product Design

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K. Hu et al., "Application of Chip-Level EMC in Automotive Product Design," *Proceedings of the 2006 IEEE International Symposium on Electromagnetic Compatibility (2006, Portland, OR)*, Institute of Electrical and Electronics Engineers (IEEE), Aug 2006.
The definitive version is available at https://doi.org/10.1109/ISEMC.2006.1706428

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Application of Chip-Level EMC in Automotive Product Design

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***Abstract*—Integrated circuits (ICs) are often the source of the high-frequency noise that drives electromagnetic emissions from electronic products. A case study is presented where emissions from a printed circuit board containing an automotive microcontroller are reduced significantly through analysis of the coupling mechanisms from the chip to the board and attached cables. Noise generated by the IC is explored through measurements in a semi-anechoic chamber and TEM cell, through near-field scans, and through modifications to the printed circuit board. Noise is driven by the IC through both power and I/O connections. Results show that a ferrite in series with I/O power in this application reduced emissions by 10 dB or more at critical frequencies. Possible causes for emissions from the IC and modifications that might reduce these emissions are discussed.**

Keywords-Electromagnetic compatibility; integrated circuits; coupling; automotive; emissions

I. INTRODUCTION

High-frequency noise from clocked circuits is inevitable. The switching of internal gates causes periodic changes in voltages and currents that create noise on power and I/O lines at the clock frequency and its harmonics. This noise drives the board and attached cables to radiate. Experience suggests, however, that there are both good and bad ICs in terms of their emissions. For example, experiments have shown there is more than a 10 dB variation in the TEM cell emissions from similar microcontrollers made by the same manufacturer [1]. Variations are likely to be even higher among different manufacturers or implementation technologies [2]. One IC may cause a particular board design to fail an emissions test while another pin-for-pin compatible IC will allow the design to pass.

The emissions driven by these ICs – that is, by the clocked components like microcontrollers and memory – are particularly challenging to deal with in automotive products. Profit margins are low, so that "standard" EMC design practices like power and return planes, filtered I/O and power lines, shielded enclosures, and even more than minimal power bus decoupling have to be approached with care to avoid unnecessary cost. In addition, electronic modules are attached to long cables and are placed very close to sensitive RF receivers, like an AM radio, so that even relatively small noise sources can be problematic. Because of potential susceptibility issues, especially to RF receivers, the emissions limits for automotive products tend to be significantly more stringent than those for other industries [3].

Issues with automotive electronics are driving standardization of methods to test and simulate integrated circuits (ICs) for EMC. Standard IEC61967, for example, defines methods to measure the potential of an IC to cause radiated emissions through conducted, capacitive, or inductive mechanisms or to radiate emissions directly from the chip [4]. The ICEM [5] and LECCS [6] models were developed to model the noise conducted through the IC power delivery network in order to facilitate better prediction of board-level emissions. Similar models are being explored to predict noise coupled through I/O [7], [8], [9].

The goal of standardized measurement and simulation techniques is not only to allow design engineers to compare different ICs, but is also to encourage IC manufacturers to produce ICs that drive less emissions. Unfortunately, many of the same issues that prevent simple EMC solutions at the board level also prevent simple solutions at the chip level. On-chip decoupling, for example, is an often-cited means of reducing emissions; however, this technique is not typically effective below the LC resonant frequency of the chip and package. Above this frequency, doubling the on-chip decoupling will often only result in a 6 dB or less reduction in emissions, but with significant potential cost due to increased die area and with reduced reliability and increased leakage current due to the additional gate oxide. In some cases, the adding decoupling may even cause an increase in emissions [10]. Similarly, the requirement that automotive ICs must function at temperatures from -40 to +150 °C means that ICs must be designed with high transition speeds to meet timing constraints at all temperature levels. Emissions have been seen to vary in TEM cell measurements by as much as 5 dB from -40 to 100 °C [1]. While we and others are developing design methods to reduce emissions, much work is still needed in this area.

As integrated circuits will continue to drive emissions for the foreseeable future, EMC engineers must continue to deal with these emissions at the board level. Simultaneously minimizing emissions and cost is challenging. While little can be done about the emissions from the IC after it is manufactured, the ability to handle these emissions can be improved considerably with a good understanding of the noise

1-4244-0293-X/06/$20.00 (c)2006 IEEE

generated by the IC and the coupling paths to the board. The following paper illustrates this concept through a case study of a microcontroller that causes system-level emissions. The microcontroller is studied in the TEM cell, in the semi-anechoic chamber, with near-field scans, and with pin-current measurements. Analysis is used to identify the dominant coupling mechanisms to the board and to mitigate coupling through minimal changes to the printed circuit board (PCB). The mechanisms responsible for the IC's emission characteristics and chip design methods for reducing emissions are also discussed.

II. INVESTIGATION OF EMISSIONS

Analysis was performed on a printed circuit board with a known emissions problem. The source of emissions was a 32-bit microcontroller used in automotive applications like the Heat, Ventilation and Air conditioning Control (HVAC), Anti-lock Braking System (ABS), electro-mechanical braking, Electronic Stability Control (ESP), and other automotive systems. Emissions occur at the system clock frequency and its harmonics. The following experiments were performed with an internal clock speed of 32 MHz (external 4 MHz), using only internal memory, and without active switching of I/O. The frequencies of interest relate to the core rather than the I/O.

Radiated emissions from the board were captured in a 3-meter semi-anechoic chamber as shown in Fig. 1. The device under test was placed on a Styrofoam pad on top of a turntable. Power was supplied through a short cable by a DC power supply. Emissions were measured with a log-periodic antenna. The output of the antenna was connected to a 25 dB pre-amplifier through a 50-ohm coaxial cable. The output of the pre-amplifier was connected to a Rohde & Schwartz FSEB spectrum analyzer and oscilloscope. Measurements were performed both with and without ferrite clamps on the power supply cable. The device was rotated and antenna polarization changed during the measurement. The maximum radiation over the test is reported.

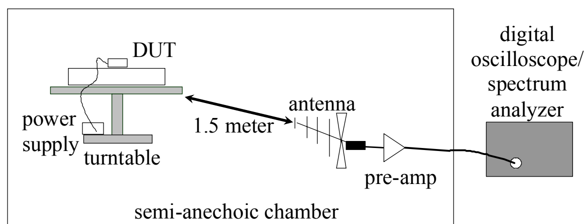

Figure 1. Measurement of emissions in 3-meter chamber.

The measured emissions are shown in Fig. 2. While not measured exactly according to the class B FCC requirements, one can readily calculate that the device is on the boundary of failing class B radiated emissions. For example, at 96 MHz, the radiated power is -47 dBm. Considering the 25 dB amplifier, a 8.2 dB(m^{-1}) antenna factor, and the measurement distance from the antenna, the measured field strength at 3 m should be approximately 40 dBuV. The class B FCC limits is 43.5 dBuV. The device would likely fail an automotive EMC test, as automotive standards are typically much more stringent than FCC requirements, especially in the 30-400 MHz band [3].

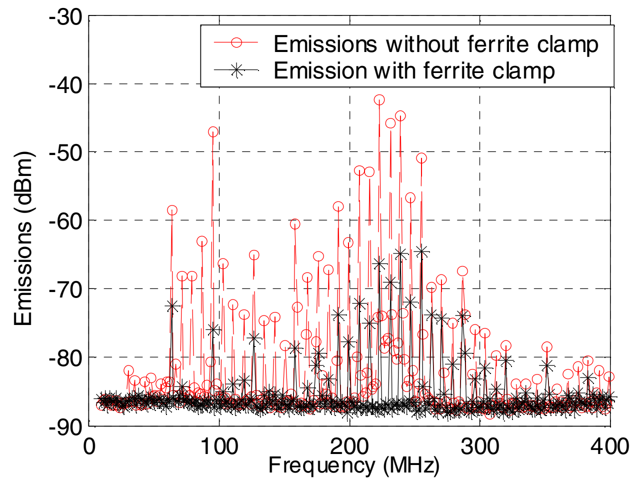

Figure 2. Measured emissions in semi-anechoic chamber from the board and power cable, with and without ferrite clamps attached to the power cable.

Eliminating emissions efficiently requires determination of the root cause of the problem. As noise occurs at the microcontroller clock frequency and its harmonics, and no other device on the PCB is clocked, the noise generator is clearly the microcontroller. The microcontroller itself, however, cannot radiate electromagnetic energy well at low frequencies because the structures on the chip and package are too small to serve as efficient antennas. Noise must be coupled to the PCB and attached cables through electric or magnetic fields or conducted through power or I/O pins, where it can then be radiated by the larger, better antennas of the system.

A. Coupling Through I/O

Noise conducted on I/O lines can be a serious problem when the I/O is attached directly to a cable. The possibility of high-frequency switching noise on low-speed I/O lines is sometimes overlooked by PCB designers. To show if noise is coupled internally from the core to the I/O and then conducted out of the package through I/O pins, measurements were performed in the semi-anechoic chamber when a 1 m cable was attached directly to the I/O and ferrite clamps were placed on the power cable. I/O were configured either as input or as output continuously driving a high or low voltage.

Measured emissions are shown in Fig. 3. Emissions with a wire attached to I/O are generally higher than when no wire is attached and the power line clamped, as shown in Fig. 2. Emissions when I/O is configured as input are much lower than when I/O is configured as output. Highest emissions are generally observed when the microcontroller is driving an output high. When the I/O drives a high or low voltage, a conduction path exists between Vddio or Vssio, respectively, and the I/O output pin. Since emissions increase on an output high or low, coupling is probably occurring between the core and Vddio or Vssio within the IC.

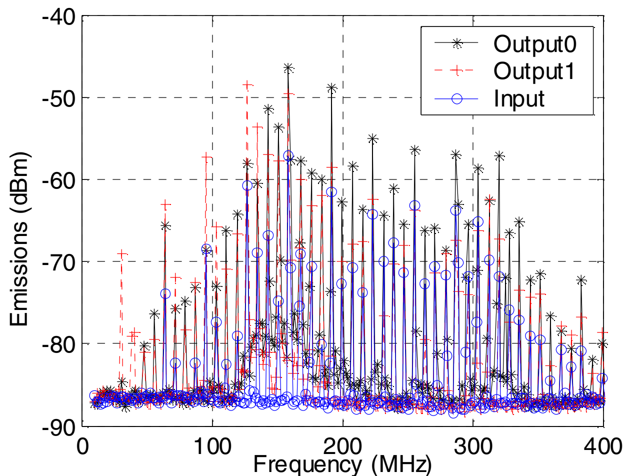

Figure 3. Measured emissions in semi-anechoic chamber from the board when a 1 m wire was attached directly to the I/O.

Two immediate solutions that could be implemented to reduce emissions from noise on I/O are to filter the I/O, especially the outputs, or to buffer the I/O before it leaves the PCB. While these solutions are likely to be effective, neither is ideal due to the extra costs involved, particularly if there are a large number of I/O. Other simpler solutions may be available. For example, if noise is being capacitively coupled from Vdd to Vddio within the chip, then noise might be reduced by better decoupling of Vdd. A better understanding of the coupling mechanisms should be acquired, however, before such solutions are pursued. One such simple solution presents itself in the next section.

B. *Coupling Through Power Pins*

Switching noise from the core may also be coupled to the board through power pin currents. Such a mechanism is indicated indirectly in Fig. 2, since no wires are attached to I/O. To further demonstrate this possibility and better understand the coupling mechanism, emissions were measured in the semi-anechoic chamber when the power cable was clamped with a ferrite and 50 cm wires were attached to the return plane of the PCB to create a dipole-like antenna, as shown in Fig. 4. Emissions were measured when the wires were attached first in the X direction then the Y direction (i.e. the attachment points were rotated 90º about the PCB).

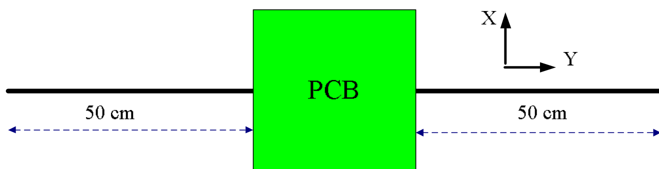

Figure 4. Wires were attached to the return plane to test the influence of power-bus noise.

As shown in Fig. 5, emissions at many frequencies tend to be lower when wires are placed in one direction compared to the other. This result indicates a possible current-driven radiation mechanism may be responsible for a significant portion of the emissions. The current-driven radiation mechanism is illustrated in Fig. 6. Current flow from the power-plane, though the IC, and back to the return plane causes magnetic flux to wrap the board. This flux induces common mode voltages that drive the board and attached cables [11]. Emissions occur when cables are oriented in the same direction as the current loop. It is reasonable to assume these currents originate from power and ground pins, since these currents are generally largest, and that currents are flowing from one side of the package to another to create a large loop area. Neither assumption, however, is guaranteed. For example, power and ground pins are typically placed next to one another. Mutual inductance between them encourages the high-frequency current entering through one pin to leave through the adjacent pin, thus creating zero net current across the package.

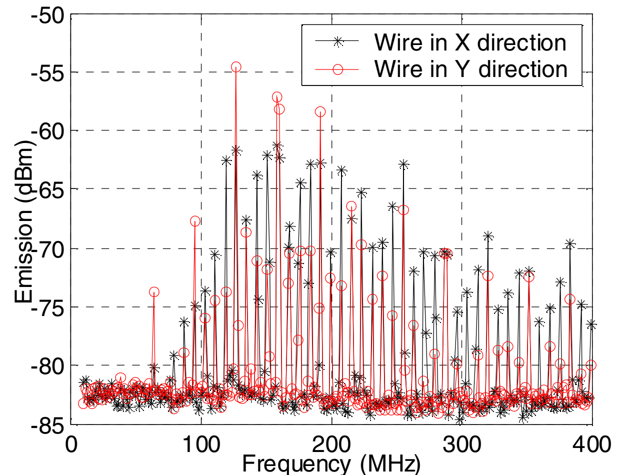

Figure 5. Measured emissions in semi-anechoic chamber when wires were attached to the return plane.

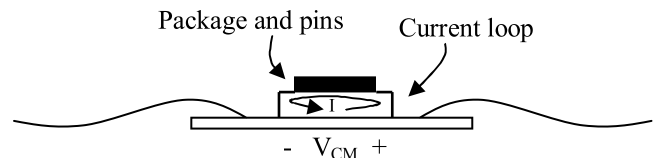

Figure 6. Current flowing across the package can cause common mode voltages and currents that drive emissions on the board and attached cables.

To validate this hypothesis, measurements of the microcontroller (alone) were taken in a TEM cell following recommendations in IEC 61967 [4]. The result is shown in Fig. 7. As expected, the same orientation relative to the attached cables that caused highest emissions in the semi-anechoic chamber also caused the highest emissions in the TEM cell.

Near magnetic-field scans above the IC were conducted to locate the source of these "common-mode" currents, following methods describe in [12], [13]. The magnitudes of the near-magnetic fields are shown in Fig. 8. Phase is shown in Fig. 9 and Fig. 10. As shown in these figures, there are particularly strong magnetic fields close to two Vddio pins and to a Vss pin. Examination of phase indicates the direction of currents. For fields in the y-direction (Fig. 9), the phase changes sign between the Vddio and Vss pin, indicating the direction of

current is changing and that current flows from the Vddio to the Vss pin. This current loop is relatively small so is unlikely to generate significant common-mode noise across the PCB. For fields in the x-direction (Fig. 10), the phase remains constant from one Vddio pin to the Vss pin, indicating current flows in one direction, from one pin to the other. This "common mode" current across the package is relatively strong and covers a large loop area, making it a prime candidate for driving emissions on the PCB, especially for wires attached in the y-direction.

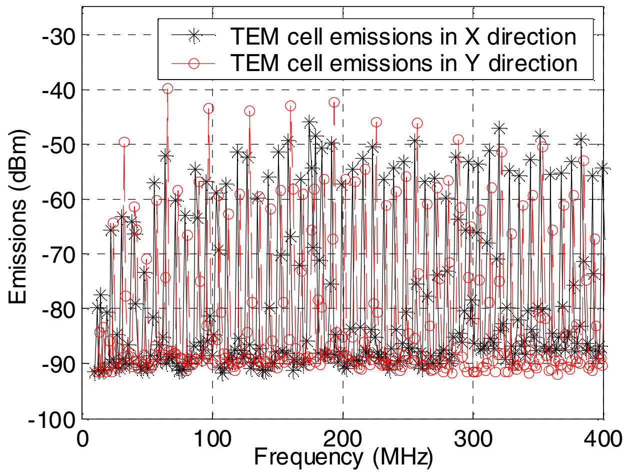

Figure 7. TEM cell emissions for two orientations of the IC.

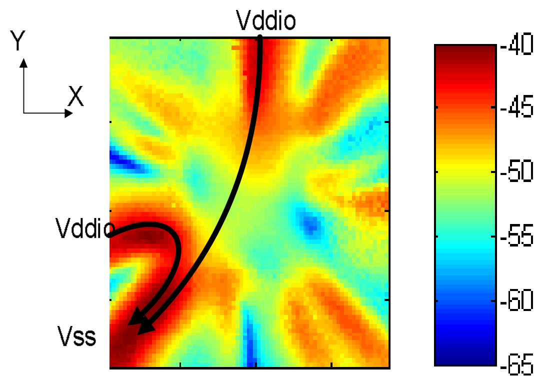

Figure 8. Magnitude in dBm of near-magnetic field over the microcontroller at 64 MHz. Currents appear to flow in the direction of the arrows shown.

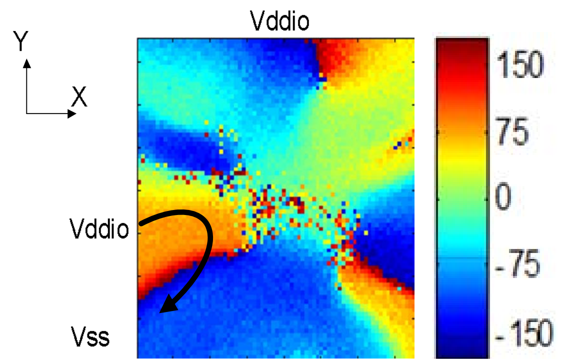

Figure 9. Phase in degrees of the near-magnetic field over the microcontroller at 64 MHz. Phase is shown for fields oriented in the y-direction (i.e. vertically for the picture shown).

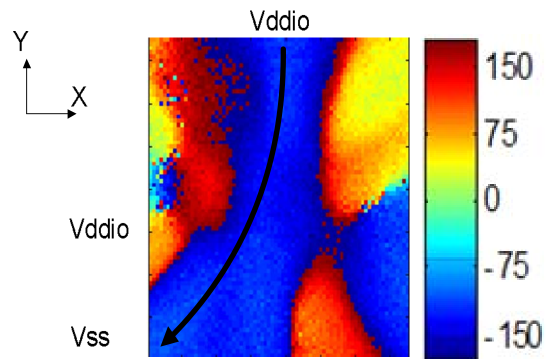

Figure 10. Phase in degrees of the near-magnetic field over the microcontroller at 64 MHz. Phase is shown for fields oriented in the x-direction (i.e. horizonatally for the picture shown).

The magnitude of currents was further verified using a specialized near-field loop probe. Since the pin-pitch of the microcontroller was very small (approximately 0.4 mm) and power and return pins were connected immediately to the power and return planes of the board, a conventional loop probe could not be used effectively. The fields measured by a loop placed on top of a pin would not measure only fields generated by that pin, but of many pins in the nearby area. To better identify currents from a single pin, a special-purpose probe was built from a slotted coaxial cable probe as shown in Fig. 11. Magnetic flux from the pin enters the slot and wraps the inner conductor. A hybrid was used to distinguish between common- and differential-mode currents and hence distinguish between inductive and capacitive coupling. Because the slot is very small, the probe is able to focus relatively precisely on the fields generated by a single pin. Measurements at 64 MHz (twice the system clock) using this probe validated near-field scan results and indicated that currents through Vddio were 20% or more of currents through Vdd. If Vdd and Vddio are internally well decoupled, then currents should be confined to Vdd.

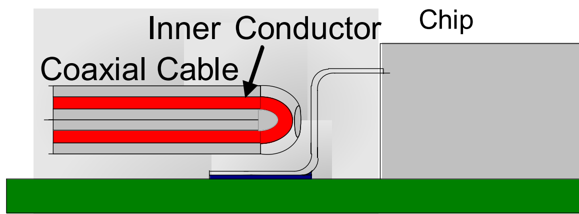

Figure 11. Slotted coaxial cable probe.

Based on these results, emissions might be reduced by either reducing the current flowing from Vddio to Vss or reducing the size of the loop. To this end, a ferrite was placed in series with the Vddio supply to increase its impedance at low frequencies (around 100 MHz). A near magnetic-field scan after inserting the ferrite is shown in Fig. 12. A strong field is now measured at the top of the IC, but now the field results from current flowing through Vssio instead of Vddio. Vddio and Vssio are right next to each other at this location. When measuring the near-magnetic field distant from the pin, as in this case where the package prevents the probe from reaching the lead frame, the near-magnetic field roughly indicates the sum of fields generated by nearby pins. In Fig. 8, fields generated by currents entering the IC through Vddio overwhelmed those generated through Vssio. After the ferrite was inserted, currents through Vssio dominated the measurement. The ferrite significantly reduced current through Vddio and redirected package currents such that the total “common mode” current flowing across the package was also reduced.

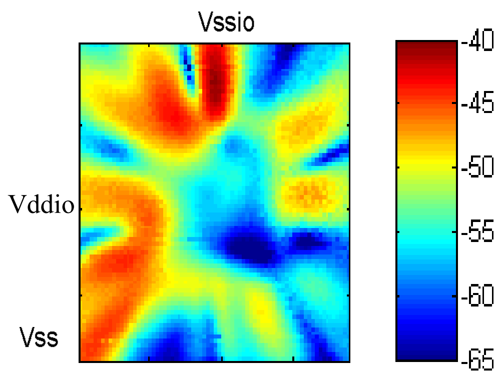

Figure 12. Magnitude in dBm of near-magnetic field over the microcontroller at 64 MHz after inserting a ferrite in series with Vddio.

Follow-up measurements in the TEM cell show that, as expected, the ferrite reduced TEM cell emissions in the Y-direction (the direction causing greatest emissions) by up to 10 dB for frequencies below 200 MHz (Fig. 13) but had little influence on emissions in the X direction. Similarly, measurements in the semi-anechoic chamber with wires attached to the power return plane in the Y direction (Fig. 14) or with power cables attached (Fig. 15) show a reduction in emissions of 10 dB or more at most frequencies below 200 MHz.

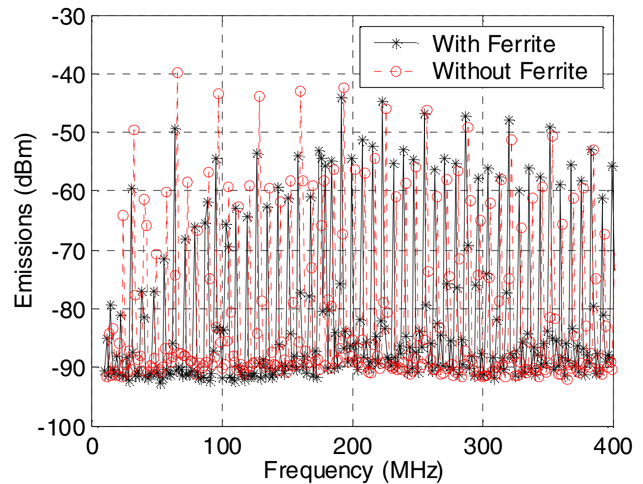

Figure 13. TEM cell emissions in Y direction with and without ferrite placed in series with Vddio.

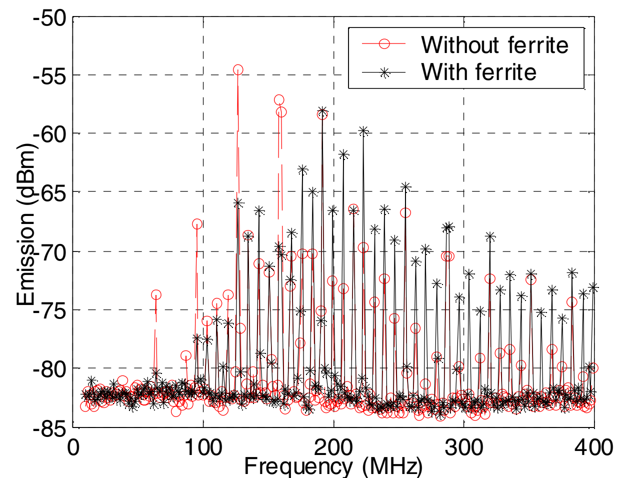

Figure 14. Measured emissions in semi-anechoic chamber when wires were attached to the return plane in the Y direction.

III. DISCUSSION

Understanding noise coupling mechanisms between the IC and printed circuit board and attached cables can be very helpful for reducing system-level emissions. Coupling mechanisms, however, may sometimes be complicated. In this case, a current-driven radiation mechanism dominated emissions at low frequencies and adding a ferrite in series with Vddio significantly reduced emissions. Even in this case, however, “obvious” reduction strategies may fail to work. Lifting the Vss pin on the bottom left of the package, through which most “common mode” currents apparently return, had less than a 2 dB influence on emissions because these currents shifted to other nearby Vss pins and caused equally bad coupling to the board. Adding a ferrite to Vddio may also not be reasonable, as it may prevent proper operation of the I/O, especially if several I/O are switching simultaneously. Identifying the current-driven radiation mechanisms, however, does significantly improve the engineer’s ability to craft a

solution. For example, since coupling occurs due to current from Vddio to Vss, one would not expect emissions to reduce with improved power-bus decoupling. For this board, removing all SMT power-bus decoupling capacitors changed emissions by only about 2 dB. At frequencies beyond 200 MHz the ferrite had little influence on emissions both because the ferrite was less resistive at higher frequencies but also because coupling mechanisms were different. Results in Fig. 5 and Fig. 7 both indicate the coupling mechanism change at higher frequencies. Near-field scans of the IC show similar results. We have not thoroughly investigated these mechanisms, but it is reasonable to assume mechanisms change as frequencies exceed the LC resonance of the chip and package, because inductance becomes an increasingly important determinant of current return paths and the relative importance of capacitive coupling from the chip to board increases.

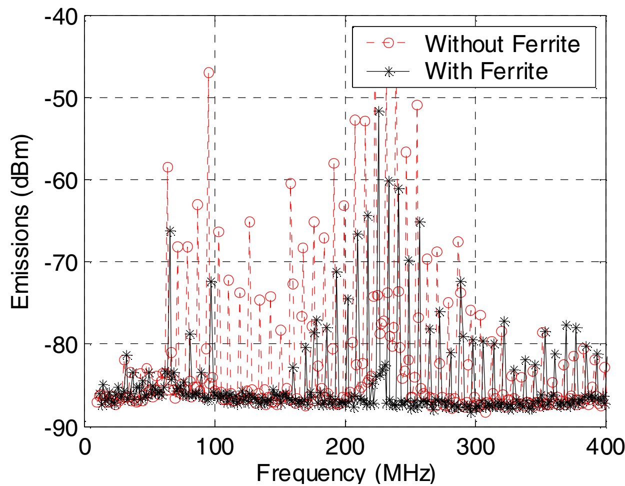

Figure 15. Measured emissions in semi-anechoic chamber when power cable was attached as normal.

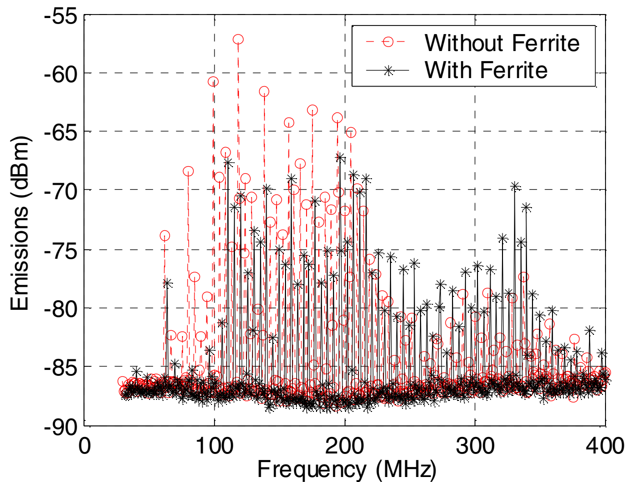

Figure 16. Measured emissions in semi-anechoic chamber when a 1 m wire was attached to an I/O input.

Emissions through I/O was dependent on the I/O configuration. When a wire was attached to I/O and I/O was set as an input, emissions dropped by about 10 dB below 200 MHz when a ferrite was added in series with Vddio (Fig. 16). When the I/O was configured as an output, however, inserting the ferrite had little influence on emissions (Fig. 17). It is possible that the same current driven mechanism dominating measurements when wires were connected to the return plane also dominated emissions when I/O was configured as input, but when the I/O was configured as output, noise conducted directly through the I/O dominated emissions. Noise on I/O outputs can present a significant challenge.

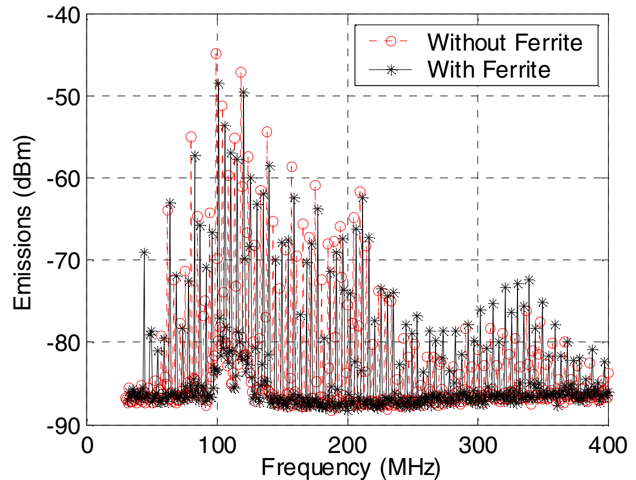

Figure 17. Measured emissions in semi-anechoic chamber when a 1 m wire was attached to an I/O output driven high.

Ideally, emissions problems could be resolved through careful IC design. In this case, however, a chip-level solution is difficult to recommend because the reasons for coupling between the core and I/O and the tendency for currents to flow through only a few power pins are poorly understood. A simple analysis of the passive characteristics of the IC does not show an obvious coupling mechanism. To analyze these mechanisms, a circuit model of the on-chip power delivery network was derived from off-chip measurements (Fig. 18). The inductance is approximate. The best return path for switching currents generated between Vdd and Vss is either on-chip, through the on-chip 8.4 nF decoupling capacitor, or off-chip, through Vdd and Vss pins. For example, say the on-board decoupling is 10 nF. At 64 MHz, the impedance seen by switching current through the Vdd/Vss pins is around 0.25 ohms. The impedances from Vdd to Vddio and from Vddio to Vss are both around 6 ohms. The current through Vdd/Vss should be many times the current through Vddio. Resonance between on-chip decoupling capacitors and package inductance can result in significant current at some frequencies, but resonance would facilitate a much more narrow-band phenomena than seen here and measurements of the IC do not support this possibility. Simulations of core-noise between Vdd and Vss similarly did not predict the noise problems observed. Preliminary investigations suggest a possible active, non-linear coupling mechanism, for example a voltage controlled current source from Vdd to Vddio/Vss resulting from parasitic PNP or NPN transistors between active P^+ or N^+ regions and the wells. Another possibility is that the distributed resistance of the

power delivery network, which can be on the order of ohms, may play a role in the current distribution at the observed frequencies. Further research is needed to investigate these hypotheses.

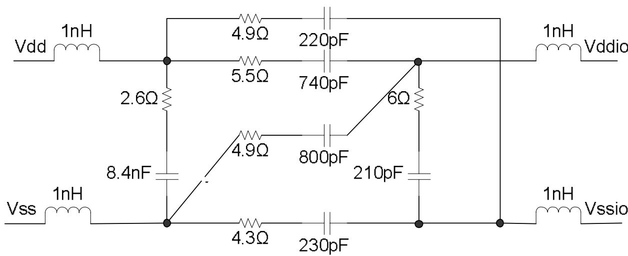

Figure 18. Circuit model of the on-chip power delivery network.

Once the on-chip coupling mechanisms are better understood, one can work to mitigate emissions through better layout and design of the IC. Emissions can be reduced by reducing the noise source, removing the coupling path from the core to I/O, or providing a better on-chip return path for noise currents [8]. While the coupling path is not known, emissions might also be reduced by reducing the noise magnitude using asynchronous logic [14] or low-power logic design [15]. A better return path for noise currents might be accomplished by adding decoupling between Vddio and Vssio, though this solution should be approached with care until the coupling mechanisms are better understood. Adding decoupling between Vdd and Vss may not help and is not an attractive solution in this case, since 8.4 nF of additional on-chip capacitance would be required to only double existing on-chip decoupling and would be prohibitively expensive. Other mitigation approaches are also possible [8].

IV. CONCLUSION

Understanding how an IC drives emissions allows one to intelligently pursue board-level emissions mitigation strategies as well as to improve IC design. Noise and coupling mechanisms can be determined through specialized measurements in the semi-anechoic chamber, through TEM cell measurements, near-field scans, pin current and voltage measurements, models of the IC, and many other techniques. Here, analysis revealed that emissions were primarily driven by a current-loop across the package. Placing a ferrite in the current path allowed emissions to be reduced by 10 dB or more at many frequencies by reducing and redistributing high-frequency currents. Such analysis techniques are also useful to the IC designer, who may use this information to reduce the source of the noise or to eliminate on-chip coupling paths.

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